Multi-Evaporator Miniature Loop Heat Pipe for Small Spacecraft Thermal Control – Part 2: Validation Results

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Under NASA's New Millennium Program Space Technology 8 (ST 8) Project, Goddard Space Fight Center has conducted a Thermal Loop experiment to advance the maturity of the Thermal Loop technology from "proof of concept" to "prototype demonstration in a relevant environment", i.e. from a technology readiness level (TRL) of 3 to a level of 6. The thermal Loop is an advanced thermal control system consisting of a miniature loop heat pipe (MLHP) with multiple evaporators and multiple condensers designed for future small system applications requiring low mass, low power, and compactness. The MLHP retains all features of state-of-the-art loop heat pipes (LHPs) and offers additional advantages to enhance the functionality, performance, versatility, and reliability of the system. An MLHP breadboard was built and tested in the laboratory and thermal vacuum environments for the TRL 4 and TRL 5 validations, respectively, and an MLHP proto-flight unit was built and tested in a thermal vacuum chamber for the TRL 6 validation. In addition, an analytical model was developed to simulate the steady state and transient behaviors of the MHLP during various validation tests. The MLHP demonstrated excellent performance during experimental tests and the analytical model predictions agreed very well with experimental data. All success criteria at various TRLs were met. Hence, the Thermal Loop technology has reached a TRL of 6. This paper presents the validation results, both experimental and analytical, of such a technology development effort.

Nomenclature/Acronym

C1	=	condenser 1
C2	=	condenser 2
CC	=	compensation chamber
CC1	=	compensation chamber 1
CC2	=	compensation chamber 2
E1	=	evaporator 1
E2	=	evaporator 2
E4	=	evaporator 4
LHP	=	loop heat pipe
MLHP	=	miniature loop heat pipe
TEC	=	thermoelectric converter
TEC1	=	thermoelectric converter 1
TEC2	=	thermoelectric converter 2

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I. Introduction

A loop heat pipe (LHP) is a very versatile heat transfer device which can transport a large heat load over a long distance with a small temperature difference [1, 2]. The LHPs currently servicing NASA and commercial orbiting spacecraft have a single evaporator with a 25-mm outer diameter primary wick [3-5]. For small spacecraft applications, miniaturization of the LHP is necessary in order to meet the stringent requirements of low mass, low power and compactness. When the heat source has a large thermal footprint, or several heat sources need to be maintained at similar temperatures, an LHP with multiple evaporators is highly desirable. Multiple evaporators also provide an inherent heat load sharing function among several heat source components [6]. Under NASA's New Millennium Program Space Technology 8 (ST 8) Project, Goddard Space Fight Center has conducted a Thermal Loop experiment to advance the maturity of the Thermal Loop technology from "proof of concept" to "prototype demonstration in a relevant environment", i.e. from a technology readiness level (TRL) of 3 to a level of 6.

The Thermal Loop is an advanced thermal control system consisting of a miniature loop heat pipe (MLHP) with multiple evaporators and multiple condensers. Each evaporator has a primary wick with 6.45 mm outer diameter. In addition, thermoelectric converters (TECs) are used to control the MLHP operating temperature. With multiple evaporators and multiple condensers, the MLHP also offers design flexibility, allowing the thermal subsystem components to be placed at optimal locations. TECs provide active heating and cooling to the MLHP compensation chambers (CCs) and allow the MLHP operating temperature to be controlled over a wider range. The MLHP retains all features of state-of-the-art loop heat pipes (LHPs) and offers additional advantages to enhance the functionality, performance, versatility, and reliability of the system.

A Thermal Loop experiment Technology Review Board (TRB), consisting of a group of independent outside LHP experts, has been assembled by the New Millennium Program Office to perform the following functions: 1) establish the criteria by which the Thermal Loop experiment will be judged to have achieved TRL 4, TRL 5, and TRL 6; 2) assess the achievement of TRL 4, TRL 5, and TRL 6 by the Thermal Loop experiment; and 3) evaluate the efficacy of the Thermal Loop experiment Technology Validation Plan.

An MLHP Breadboard was built and tested in the laboratory and thermal vacuum environments for the TRL 4 and 5 validations, respectively, and an MLHP proto-flight unit was built and tested in a thermal vacuum chamber for the TRL 6 validation. In addition, an analytical model was developed to simulate the steady state and transient operation of LHPs. The Thermal Loop concept, technical advances and benefits, objectives, Level 1 requirements, performance characteristics, analytical model, and the validation approach to verify the attainment of TRL 6 by the Thermal Loop experiment were described in a separate paper.

This paper presents the validation results, both experimental and analytical, of the Thermal Loop technology development. The MLHP Breadboard used for TRL 4 and TRL 5 validations will be described first. Results of TRL 4 and TRL 5 validations are presented next. This will be followed by the description of the MLHP proto-flight unit used for TRL 6 validation, and the validation results.

II. MLHP Breadboard

The New Millennium Program defines TRL 4 as "component and/or breadboard validated in a laboratory environment" and TRL 5 as "component and/or breadboard validated in a relevant environment." For the Thermal Loop experiment, an MLHP Breadboard as shown in Figure 1was built and tested for both TRL 4 and TRL 5 valdiation. Major design parameters of the MLHP are summarized in Table 1.

The MLHP Breadboard consisted of two parallel evaporators – each with an integral CC, two parallel condensers, a common vapor transport line and a common liquid return line. A thermal mass of 400 grams of aluminum was attached to each evaporator to simulate the instrument mass. A cartridge heater capable of delivering 1W to 200W was inserted into each thermal mass. Each condenser was serpentined and sandwiched between two aluminum plates. Each set of aluminum plates was made into a semi-circular shape so that the entire MLHP Breadboard could be placed inside a thermal vacuum chamber for TRL 5 testing. A flow regulator consisting of capillary wicks was installed at the downstream of the two condensers. The vapor line and liquid line were connected with several aluminum coupling blocks (20 mm by 20mm by 6mm each). The number of aluminum blocks could be varied during experimental investigations. The evaporators and CCs were about 100 mm apart from the condensers. The MLHP was charged with 29.3 grams of anhydrous ammonia.

A TEC was installed on each CC through an aluminum saddle. The other side of the TEC was connected to the evaporator via a copper thermal strap. The TECs were made by Marlow Industries, Inc. with a model number of DT3-6. A close-up view of the evaporator/CC section showing the TECs and thermal straps is depicted in Figure 2.

Table 1. Summary of MLHP Breadboard Design Parameters

Component	Material	Value
Evaporators (2)	Aluminum 6061	9 mm O.D. x 52 mm L
Primary Wicks (2)	Titanium	6.35 mm O.D. x 3.2mm I.D Pore radius 1.39 μm (E1), 1.47 μm (E2) Permeability: 0.11 x 10^{-13}m^2 (E1), 0.09 x 10^{-13}m^2 (E2)
Secondary Wicks (2)	Stainless Steel	Pore radius: 68.7 μm Permeability: 83 x 10^{-13}m^2
Bayonet Tubes (2)	SS 304L	1.1 mm O.D. x 0.79 mm I.D.
CC (2)	SS 304L	22.2 mm O.D. x 21.2 mm I.D. x 72.4 mm L
Vapor Line	SS 304L	2.38 mm O.D. x 1.37 mm I.D. x 914 mm L
Liquid Line	SS 304L	1.59 mm O.D. x 1.08 mm I.D. x 914 mm L
Condensers (2)	SS 304L	2.38 mm O.D. x 1.37 mm I.D. x 2540 mm L
Flow Regulator	SS	Pore radius: 10.1 μm Permeability: 3.1 x 10^{-13}m^2
Working fluid	Ammonia	29.3 grams
Total LHP mass		316.6 grams

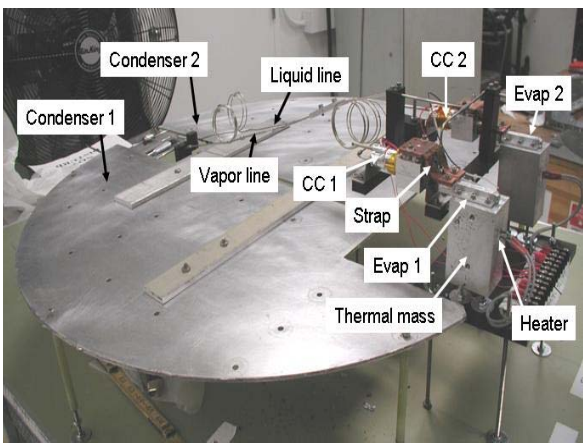

Figure 1. Picture of the MLHP Breadboard

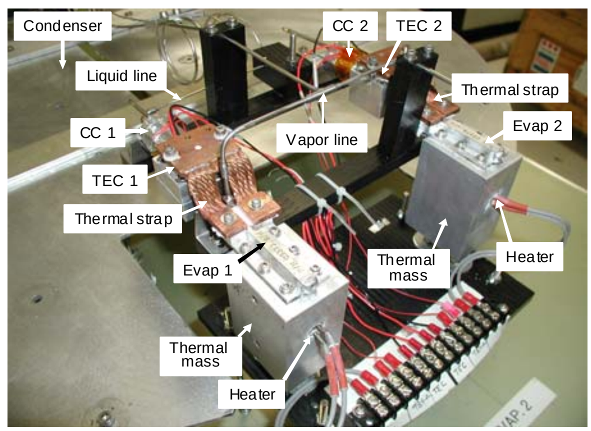

Figure 2. Close-up View of Evaporator/CC Section

III. TRL 4 and TRL 5 Validations

Test Set-up: In laboratory testing, the MLHP was placed on a test frame, which could be rotated to allow the MLHP to be tested at various orientations. Cooling of the condensers was provided by two chillers, one for each condenser. Each chiller could be maintained at a desired set point temperature, independent of each other. Two other chillers were used to cool the evaporator thermal masses during the heat load sharing test, but only one chiller was needed for any given heat load sharing test. By measuring the flow rate and the temperatures at the inlet and outlet ends of the fluid flow through the thermal mass, the amount of heat being shared could be calculated. The heat load to each evaporator thermal mass was derived from the measured voltage and current. Each TEC was controlled by a bi-polar power supply. Changing the polarity of the power supply changed the TEC operation between the heating and cooling modes. In addition, an electric heater was istalled on each CC for temperature control. Either the TEC or the electric heater was used to controll the CC temperature for a given test, but not both. The control heater power savings using TEC versus electric heater could thus be evaluated. In order to investigate the effect of coupling blocks on CC temperature control, various numbers of coupling blocks (0, 1, 2 and 3) were used.

The test set-up for TRL 5 validation testing in a thermal vacuum chamber was similar to that in the laboratory environment except: 1) Each radiator was cooled by a cryopanel through radation on one side (the down-facing side). Two copper cryopanels were used as radiator sinks, one for each radiator. Temperatures of the two cryopanels were set to be the same, ranging from 123K to 303K, depending on the type of test performed, although they could be changed independently. 2) Four supplemental heaters were installed on both radiators on the up-facing sides. These supplemental heaters were activated, when needed, to prevent the ammonia working fluid from freezing. They could be independently controlled at different set point temperatures for various tests, such as the flow regulation test; 3) Multi-layer insulation was used between the top side of the radiator and the rest of the MLHP components (evaporators, CCs, vapor line, and liquid line and thermal masses. 4) One chiller placed outside the thermal vacuum chamber was used to circulate a coolant flow through the evaporator thermal mass during the heat load sharing test. Because only one thermal mass needed to be cooled at a time, two valves were used to direct the coolant from the chiller to the intended thermal mass. 5) The MLHP Breadboard was tested in two orientations only: horizontal and vertical. In the horizontal position, all components were placed horizontally and the evaporators/CCs were about 100mm above the condensers. In the vertical position, the evaporators/CCs were placed at the top.

More than 120 type T thermocouples were used to monitor the MLHP and the coolant flow temperatures. Additional thermocouples were added to the radiators and cryopanels in the thermal vacuum test. Figure 3 shows the thermocouple locations for the thermal vacuum test. A data acquisition system consisting of a data logger, two personal computers, and two screen monitors was used to collect, display, and store temperature and power data every second. LabView software was as used for the command and control of the test conditions.

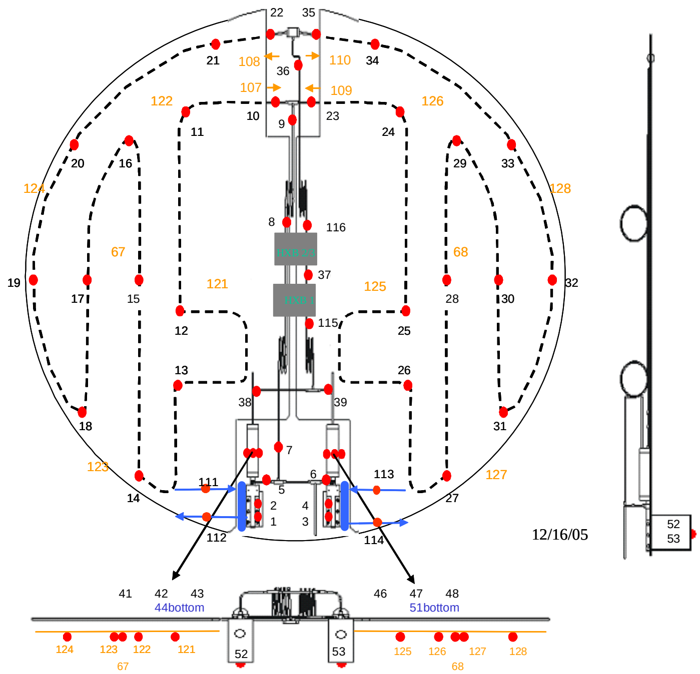

Figure 3. MLHP Breadboard Thermocouple Locations

TRL 4 Validation Results: The MLHP Breadboard was tested in the laboratory under five different orientations where the two evaporators/CCs and the two condensers were placed at different tilts and elevations relative to one another. More than 1200 hours of experimental data was collected. These tests included start-up, power cycle with even and uneven powers to the two evaporators, sink temperature cycle, flow regulation, high power, low power, and heat load sharing. Tests were conducted with or without controlling the CC saturation temperature. For tests where the CC temperature was controlled, electric heaters, one TEC, or two TECs were used to control the respective CC. The loop demonstrated excellent performance: 1) All start-up tests were successful. The loop could start successfully with heat loads between 5W and 100W, 2) The loop operating temperature was controlled within ±1K of the CC set point temperature ranging from 283K to 313K using TECs or electrical heaters; 3) The two evaporators/thermal masses could share heat load when one of them was not powered; 4) The flow regulator could stop the vapor from entering the liquid line when one of the condensers exhausted it heat dissipating capability; 5) The use of TECs for temperature control saved more than 50% of the control heater power when compared to electrical heaters; 6) The effect of gravity on loop start-up, heat load sharing and capillary limit were verified; 7) The loop demonstrated stable operation under all test conditions; 8) The loop could transport more than 120 W of heat load; and 9) The analytical model predictions agreed very well with the experimental data. The MLHP successfully validated the attainment of TRL 4. Results of these tests were presented in previous papers [7-12]. Because of space limitation, this paper will focus on TRL 5 and TRL 6 validation results.

TRL 5 Validation Results: More than 500 hours of experimental data was collected for TRL 5 validation. The MLHP Breadboard demonstrated excellent performance and the LHP analytical model predictions agreed very well with experimental data. Table 2 shows the TRL 5 requirements/success criteria and the validation results. All TRL 5 success criteria were met or exceeded. Thus, the Thermal Loop technology attained TRL 5. The TRL 5 validation results have been described in previous papers [13-15]. Some highlights are presented below.

Table 2. TRL 5 Success Criteria and Validation Results

Test	Requirement/Success Criteria	TRL 5 Validation Results	Compliance
Start-up	• An 80% success rate or better on a minimum of 20 start-ups • Demonstrate over a temperature range between 273K and 308K	• 100% success on 72 start-up tests • Temperature range between 258K and 308K	Exceed requirements
Heat Transport	• 75W total heat load	• 120W total heat load	Exceed requirements
Operation	• Control the loop saturation temperature within ±3K between 273K and 308K • Transient operation over full range of heat loads	• Control the loop saturation temperature within ±0.5K between 258K and 308K • Transient operation between 5W and 120W with rapid changes of heat load and/or sink temperature • Changed saturation temperature between 258K and 308K while in operation	Exceed requirements
Heat Load Sharing	• Demonstrate heat load sharing between two evaporators (0W to 75W)	• Heat load sharing was demonstrated by changing 1) heat load to one evaporator (0W to 100W); 2) sink temperature of un-powered evaporator; and 3) CC saturation temperature	Exceed requirements
LHP Model Correlation	• Model predictions of LHP critical temperatures within ±5K of the test results during steady state and transient operation	• Model predictions of the loop critical temperatures (CCs, evaporators, vapor and liquid lines) were within ±5K of the test results during steady state and transient operation.	Meet requirement

A problem was encountered during thermal vacuum testing. For some unknown reasons, sporadic data drops occurred. At every event of the data drop, all temperatures read 282K for a single data scan. In response to the erroneous CC temperature reading, the TECs would either cool or heat the CC in an attempt to bring the CC temperature to the desired set point. As a result, the CC temperature fluctuated about ±1K for a few minutes until stable temperatures were reestablished. The TECs could quickly bring the CC temperature to its original set point. In the following descriptions of test results, the effect of such data drop can be clearly seen. For clarity, the single point of data drop was eliminated in all plots. Furthermore, in all plots, numbers in the parentheses denote the thermocouple locations shown in Figure 3.

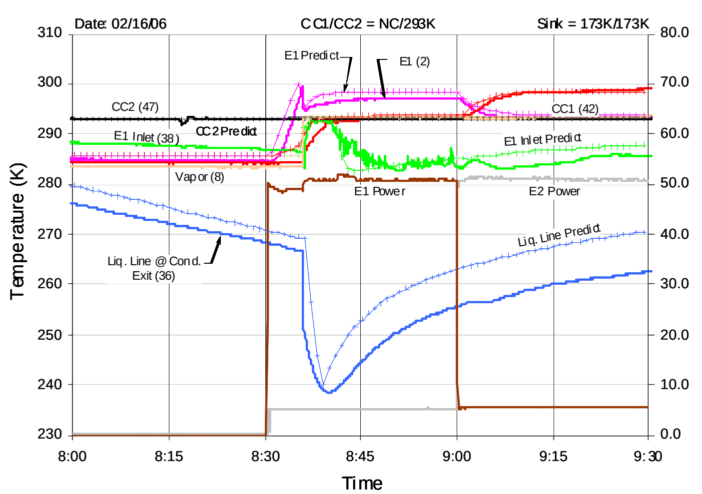

Figure 4. MLHP Breadboard Temperatures for Start-up with 50W/5W to E1/E2

Figure 4 illustrates the loop temperature in a start-up test with a heat load of 50W/5W to E1/E2. Initially, CC2 was pre-heated to 293K. A heat load of 50W/5W was then applied to E1/E2 thermal masses. Because E1 had a much higher heat load, its temperature rose more quickly than E2. When the E1 temperature reached 296K, the loop started with a superheat of 3K. After the loop started and vapor was generated in E1, some of the vapor flowed to E2 via the heat load sharing mechanism. Thus the E2 temperature rose more quickly to 293K. Both E1 and E2 temperatures became steady after the start-up transient. Note that the E1 temperature was higher than the E2 temperature due to a higher heat load (heat flux). The heat load was then changed to 5W/50W. Because of the higher heat load, E2 showed a higher temperature than E1. The analytical model predictions of the loop temperatures are also shown in Figure 4. The model accurately predicted the transient events and the temperature predictions agreed very well with the experimental results.

Start-up with high powers to the evaporators such as the one shown in Figure 4 is usually not a problem. Low power start-up could be more challenging because the heat leak and possible superheat that is required for vapor generation. Figure 5 shows the loop temperatures during a start-up test with 10W to E2. Prior to the start-up, both CC1 and CC2 were per-heated to 293K so that the evaporators were flooded with liquid. When a heat load of 10W was applied to E2, the E2 temperature began to rise. When the E2 temperature rose above 293K, the loop started as indicated by a sudden drop of the liquid line temperature. Before the loop started, the E1 temperature remained at 287K. After the loop had started, the E1 temperature gradually rose to 293K because E1 drew heat from E2 by way of heat load sharing. It can be seen that the LHP analytical model predicts all the transient events accurately, and the model predictions agreed very well with the experimental data.

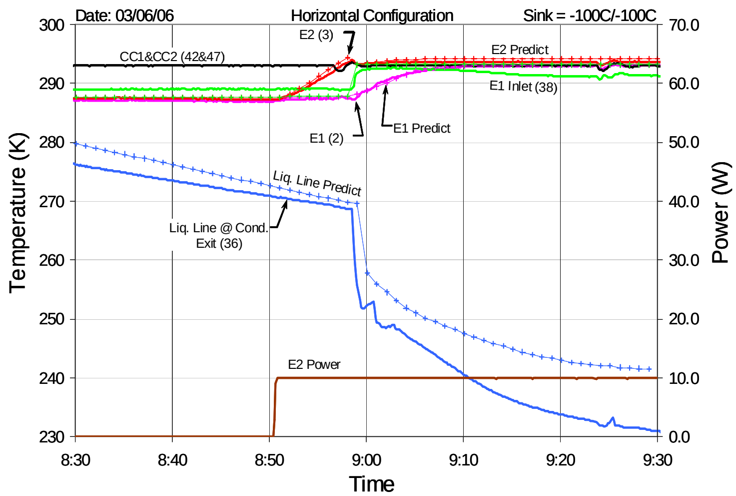

Figure 5 Loop Temperatures in a Start-up in the Thermal Vacuum Chamber (293K)

The TECs provided active heating and cooling to the CCs, and maintained the CCs at a fixed temperature during the start-up transient, thereby enhancing the success of LHP start-up. Furthermore, the TECs made it possible to start the loop by lowering the CC temperatures below the evaporator temperatures [14]. Figure 6 shows that, using TECs, the CC temperatures were lowered from 293K to 258K in steps with 5K increments at each step. The cryopanels were set at 173K/173K throughout the test. The loop actually started when the CC temperatures were lowered to 288K. The loop was operational because temperatures of the evaporators, transport lines, and thermal masses all moved in tandem with the change of the CC temperatures. The heat input to the evaporators came from several sources, including parasitics, power that was applied to the TECs, and the heat that was pumped out of the CCs. Once the loop was running, an additional heat source came from the release of the sensible heat by the thermal masses. Because the loop had already started, when a heat load of 10W/10W was applied to E1/E2, the event was simply a change of the heat load so far as the loop was concerned. It should be noted that the operation of temperature step-down depicted in Figure 6 was not possible if electrical heaters alone were used to control the CC set point temperature because the electrical heaters were incapable of providing active cooling to the CCs whose surrounding temperature was 285K.

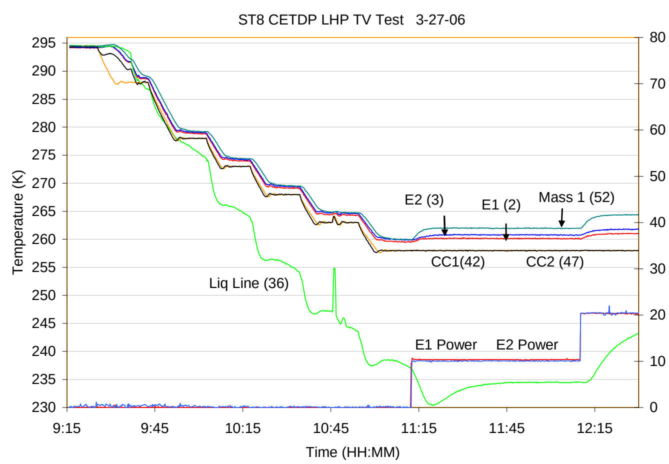

Figure 6. CC Set Point Change and Loop Operation at 258K

One of the advantages of a two-phase thermal system such as an LHP is that the operating temperature can be changed while the loop is operational. Using electrical heaters, the CC set point temperature can be adjusted as long as the temperature is above the LHP natural operating temperature. In contrast, a TEC can afford the LHP to operate at a temperature lower than its natural operating temperature because of its ability to provide active cooling. Figure 7 depicts the loop temperatures during a CC set point change test where a heat load of 10W/10W was applied to E1/E2, and the cryopanels were kept at 223K/223K. The CC1/CC2 temperatures were changed in steps: 293K/293K, 288K/288K, 283K/283K, 278K/278K, and 273K/273K using both TECs. As the CC1/CC2 set points were changed, temperatures of E2 and vapor line followed the change. For clarity, the E1 temperature is not shown in the figure, but it was almost the same as the E2 temperature. After the loop had been operating at 273K for about 30 minutes, both TECs were turned off, and the loop gradually approached its natural operating temperature around 282K. Both evaporators and the vapor line followed the change. This test clearly illustrated that, using TECs, the loop could operate at temperatures below its natural operating temperature.

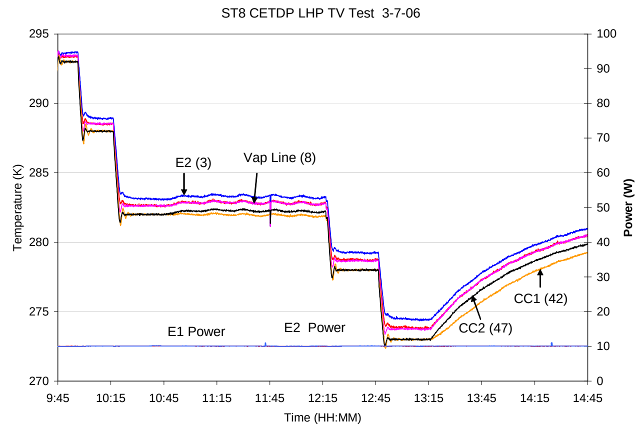

Figure 7. CC Set Point Change Test

Figure 8 shows the loop temperatures in a high power test. Both cryopanels were kept at 123K, and both CCs were controlled at 308K using TECs. The initial heat load to E1/E2 was 10W/10W, and then increased to 60W/60W with 10W/10W increments. The loop demonstrated a heat transport capability of 120W. The TECs controlled the CC temperatures within ±0.5K at all times except for the periods following data drops where the CC temperature fluctuated ±1K for a short duration before TECs resumed tight control of the CC temperatures. Temperatures of E1/E2 varied with the heat load. At 60W/60W, E1 began to show partial dry-out as indicated by a sudden, large increase of its temperature. When the heat load was reduced to 40W/40W, E1 recovered from the partial dry-out.

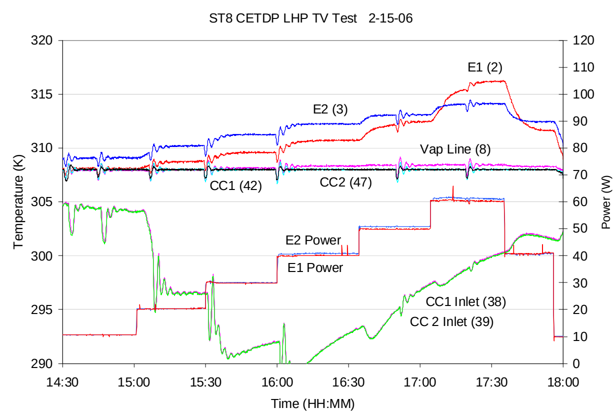

Figure 8. High Power Test

The flow regulator in the MLHP was designed to prevent vapor from entering the liquid line when one of the condensers had exhausted its heat dissipating capability provided the other condenser could still dissipate the total heat load. Figure 9 depicts the loop temperatures during a flow regulation test. Both CCs were controlled at 293K using TECs and a constant heat load of 30W/10W was applied to E1/E2. Both cryopanels were maintained at 173K. Tests were conducted by changing the set point temperature of control heaters on one radiator while keeping the set point of control heaters on the other radiator constant at 223K. In the first part of the test, the set point temperature of Radiator 1 heaters was varied from 223K to 293K and then to 298K. When control

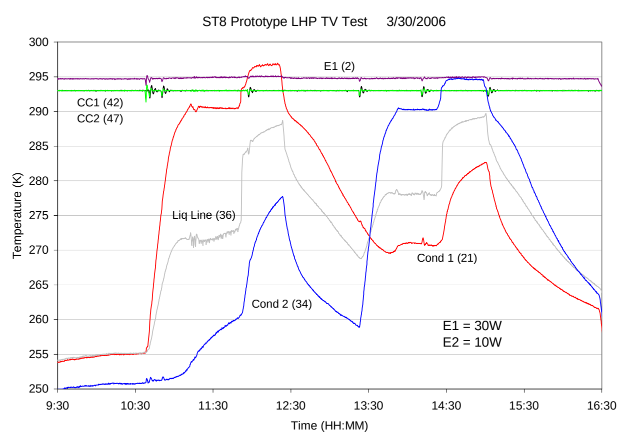

Figure 9. Flow Regulation Test

heaters on both radiators were set at 223K, temperatures of both condensers and the liquid exiting the flow regulator (TC36) were below 255K, indicating that neither condenser was fully utilized. When Radiator 1 was heated to 293K, Condenser 1 dissipated much less heat than Condenser 2. Condenser 2 also rose in temperature because its heat load increased. When Radiator 1 was heated to 298K, above the CC saturation temperature, Condenser 1 could no longer dissipate any heat, and vapor extended to the exit of Condenser 1. However, the vapor was stopped by the flow regulator, as evidenced by the subcooled temperature of TC36. In the second part of the test, the set point temperature of Radiator 1 control heaters was kept at 223K whereas the set point of Radiator 2 control heaters was varied between 223K and 298K. Similar results were observed. This test demonstrated that the flow regulator performed its function as designed.

Figure 10 shows the loop temperatures in a heat load sharing test. The analytical model predictions are presented along with the experimental data. The CC1 temperature was controlled at 303K. A constant heat load of 50W was applied to E2. After a successful start-up, a coolant flow was circulating through the E1 thermal mass to initiate heat load sharing. The temperature of the circulating coolant was then gradually increased while the mass flow rate remained unchanged. The heat being shared by E1 was calculated from the measured temperatures of the fluid entering and leaving the E1 thermal mass. When the temperature of the circulating coolant was raised, the E1 thermal mass would dissipate less heat, resulting in less heat being shared by E1. When the temperature of the coolant was raised above the CC saturation temperature, E1 automatically switched its operation from the condenser mode to the evaporator mode, and the heat being shared became negative, indicating a net heat input from the coolant to E1. The model predictions of the loop temperatures and the amount of heat being shared by E1 were in excellent agreement with the test results.

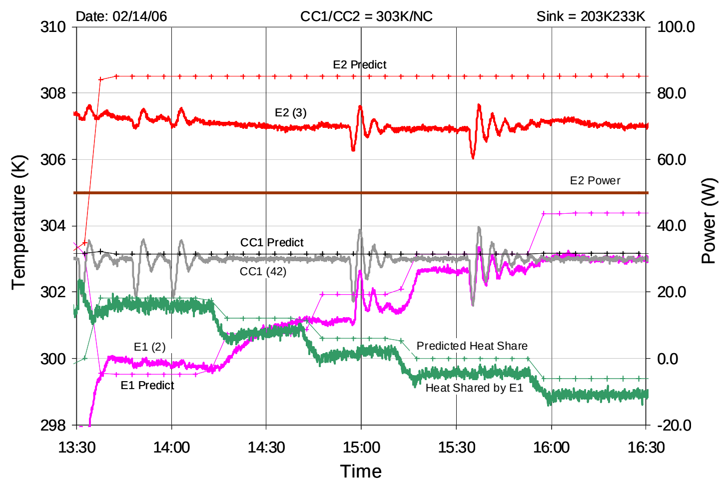

Figure 10. Loop Temperature in Heat Load Sharing Test

V. MLHP Proto-flight Unit

The New Millennium Program defines TRL 6 as "system/subsystem model or prototype demonstration in a relevant environment on the ground or in space." An MLHP proto-flight unit, as shown in Figure 11, was built and tested for TRl 6 validation. Major design parameters are presened in Table 3. The proto-flight unit was originally planned to be mounted on the ST 8 spacecraft for a space flight experiment for the TRL 7 validation. Unfortunately, NASA later canceled the flight segment of the ST 8 Project due to budget constraints. The designs of the evaporator, CC, condensers, vapor line, and liquid line are the same as those in the MLHP Breadbord except: 1) The length of the vapor line, liquid line and condenser were 1580 mm, 1120 mm and 1676 mm, respectively; 2) The two radiators were rectangular, each having a surface area of 432mm x 317 mm; 3) Each condenser was serpentined and embedded in the

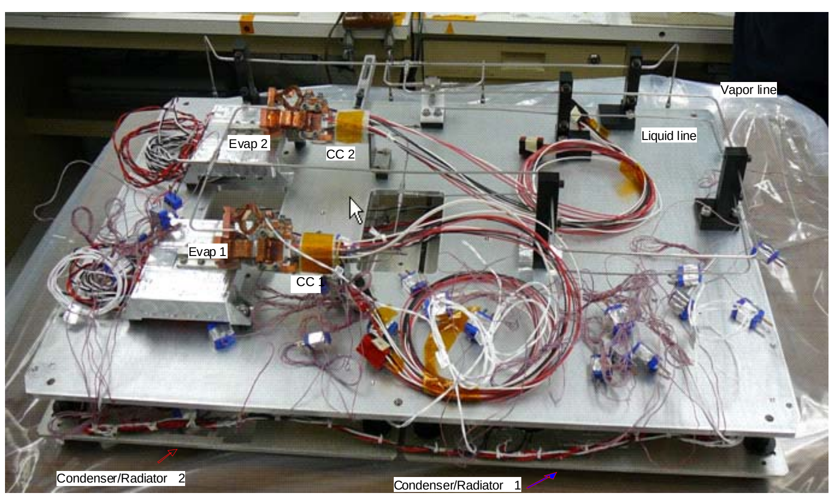

Figure 11. Picture of the MLHP Proto-flight Unit

radiator; 4) The TEC was mounted on a saddle attached to the CC and a flexible thermal strap was used to connect the TEC to the evaporator; 5) Two TEC assemblies were used for each CC to provide redundancy; 6) To investigate the effect of thermal masses on the MLHP transient responses, a 540-gram aluminum thermal mass was attached to Evaporator 1 and a 280-gram aluminum thermal mass was attached to Evaporator 2; 7) the loop was charged with 31.3 grams of anhydrous ammonia; and 8) Each evaporator was mounted on a thermal mass, and the thermal masses, CCs, and transport lines were mounted on a base plate with standoffs supporting the transport lines. The base plate and the radiators were 152 mm apart, and multi-layer insulation was placed in this space during the thermal vacuum test so as to insulate the base plate from the radiators.

Table 3. Primary Design Parameters of MLHP Proto-flight Unit

Component	Material	Value
Evaporators (2)	Aluminum 6061	9 mm O.D. x 52 mm L
Primary Wicks (2)	Titanium	6.35 mm O.D. x 3.2mm I.D. Porosity: 0.35 Hydraulic diameter of vapor groove (equivalent): 1.27 mm Pore radius 1.25 μm (E1), 1.20 μm (E2) Permeability: 0.8 x $10^{-14}m^2$ (E1), 1.0 x $10^{-14}m^2$ (E2)
Secondary Wicks (2)	SS 304L	Pore radius: 45.53 μm (E1), 36.04 μm (E2)
Bayonet Tubes (2)	SS 304L	1.1 mm O.D. x 0.80 mm I.D.
CC (2)	SS 304L	22.5 mm O.D. x 21.2 mm I.D. x 76.7 mm L
Vapor Line	SS 304L	2.38 mm O.D. x 1.37 mm I.D. x 1580 mm L
Liquid Line	SS 304L	1.59 mm O.D. x 1.08 mm I.D. x 1102 mm L
Condensers (2)	SS 304L	2.38 mm O.D. x 1.37 mm I.D. x 1676 mm L (each)
Flow Regulator	SS 316L shell and wicks	Pore radius: 9.35 μm, 13.83 μm Permeability: 9.11 x $10^{-13}m^2$, 9.49 x 10^{-13} m^2
Working Fluid	Anhydrous Ammonia	31.3 grams

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VI. TRL 6 Validation

Test Set-up*:* For TRL 6 validation, the MLHP proto-flight unit was placed inside the same vacuum chamber used for the MLHP Breadboard TRL 5 validation test, and the test set-up for TRL 6 validation test was very similar to that for the TRL 5 test. The differences are: 1) Each CC had two TECs attached, and CC temperature control could be accomplished by using either TEC. Only one bi-polar power supply was used to control a TEC. Connecting an individual TEC to the power supply was done manually; and 2) No chiller outside the chamber was used for the heat load sharing test. The heat load sharing test was performed by applying power to one evaporator thermal mass and by raising the CC set point temperature in steps.

More than 120 type T thermocouples were used to monitor the temperatures of the MLHP, radiators, and cryopanels. Figures 12 and 13 show the thermocouple locations. Note that the thermocouple numbers are not consecutive. A data acquisition system consisting of a data logger, two personal computers, and two screen monitors was used to collect, display, and store temperature and power data every second. LabView software was as used for the command and control of the test conditions.

Validation Results*:* During the TRL 6 validation testing of the MLHP proto-flight unit, it was found that Evaporator 2 was damaged and could transport only 60W of heat load. By contrast, Evaporator E1 could transport more than 100W of heat. The exact cause of the E2 damage was not known, but most likely occurred between the time when the unit was delivered to GSFC and when the unit was being prepared for the thermal vacuum test. The schedule constraint demanded that testing of the proto-flight unit be continued with tests that did not require more than 60W of E2 power. At the same time, a replacement evaporator (Evaporator E4) was fabricated. After E4 was integrated into the proto-flight unit, the unit was tested again in the same vacuum chamber for those tests requiring more than 60W to E4. In the following discussions, E2 or E4 was clearly labeled in the data plots so there should be no misunderstanding when E2 or E4 was used in a given test. The same success criteria and test results listed in Table 2 also applied to the proto-flight unit for the TRL 6 validation. The prtoflihgt unit met or exceeded all of the requirements. The LHP analytical model predictions also showed excellent agreements with experimental data. The attainment of TRL 6 by the Thermal Loop experiments was therefore successfully validated. Some validation results are highlighted below.

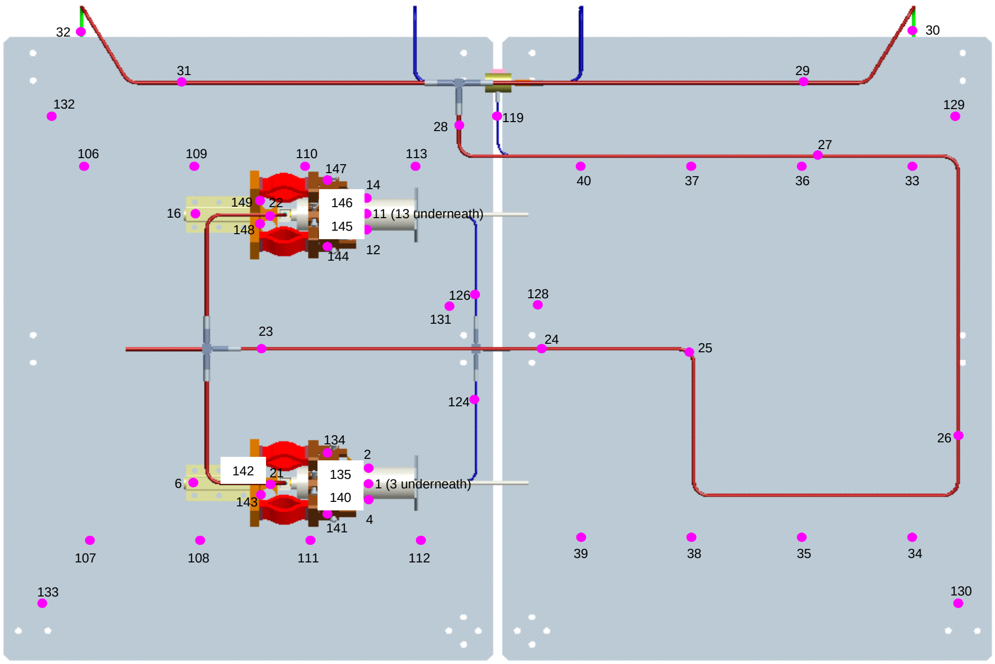

Figure 12. Thermocouple Locations (Overall) on MLHP Proto-flight in TV Testing

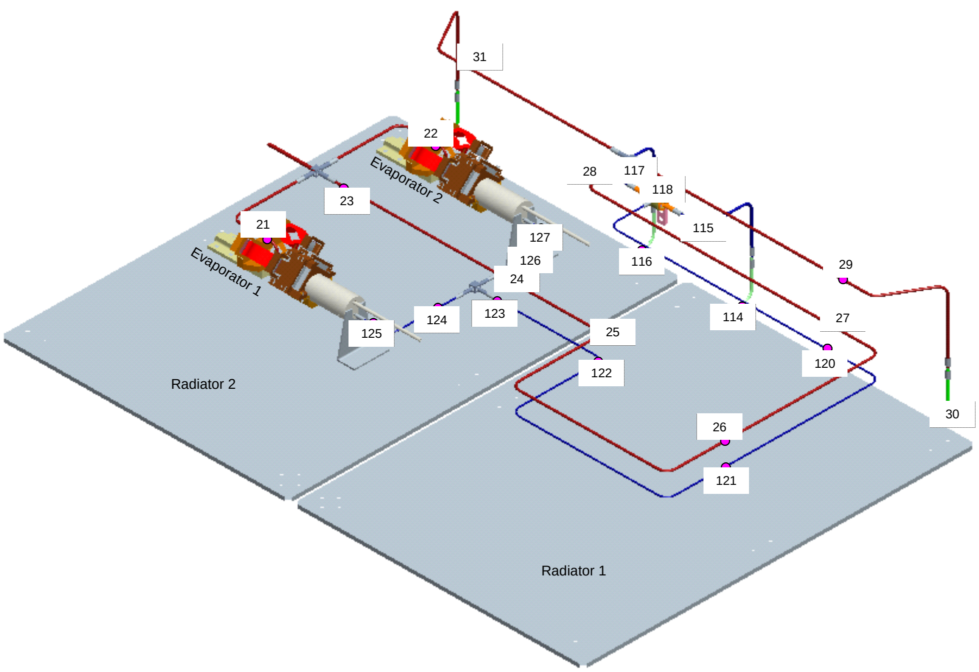

Figure 13. Thermocouple Locations on the Transport Lines of the Proto-flight in TV Testing

Figure 14 depicts the temperatures in a start-up test where CC1/CC2 temperatures were maintained at 273K. Also shown are the analytical model predictions. Initially the loop components were kept at around 263K except for the CCs which were kept at 273K. A heat load of 50W was then applied to E2. When the E2 temperature reached 276K, the loop started with 3K superheat. With such a high heat load, not only did the E2 temperature rise quickly during the warm-up period, but E1 also shared heat from E2 soon after the loop started. The experimentally observed superheat of 3K was used as an input parameter to the analytical model. It is seen that the model accurately predicted all major events, and the predicted temperatures were within ±5K of the experimental results.

As mentioned previously, LHP start-up with a low power could be difficult. The MLHP proto-flight unit demonstrated successful start-up between 273K and 308K with heat loads to E1/E2 of 10W/0W, 0W/10W, 5W/5W, 5W/0W, and 0W/5W. Figure 15 shows the loop temperatures for a 5W/0W start-up at 293K. Initially, the E1/E2 and vapor line temperatures were below 288K, and CC1/CC2 temperatures were maintained at 293K using TECs. As 5W was applied to the E1 thermal mass, the E1 temperature rose gradually. When E1 reached 295K, the loop started with a 2K superheat. After the loop started, the E2 temperature also increased because of heat load sharing. With only 5W to E1, the amount of heat that could be shared by E2 was small, and the E2 temperature rose very slowly.

Figure 16 shows the loop temperatures for a high power test where the cryopanels were maintained at 173K and the temperatures of both CCs were not controlled. Even heat loads were applied to E1/E4 from 20W/20W to 70W/70W. Both CC1 and CC2 temperatures varied with the heat loads. Test results showed that CC2 controlled the loop operating temperature and CC1 was hard filled with liquid. The E1 and E4 temperature varied with the CC2 temperature and the heat load. The loop could transport 60W/60W without any problem. At 70W/70W, the CC temperatures rose rapidly, an indication that vapor has penetrated the evaporator wick, i.e. the loop had exceeded its capillary limit.

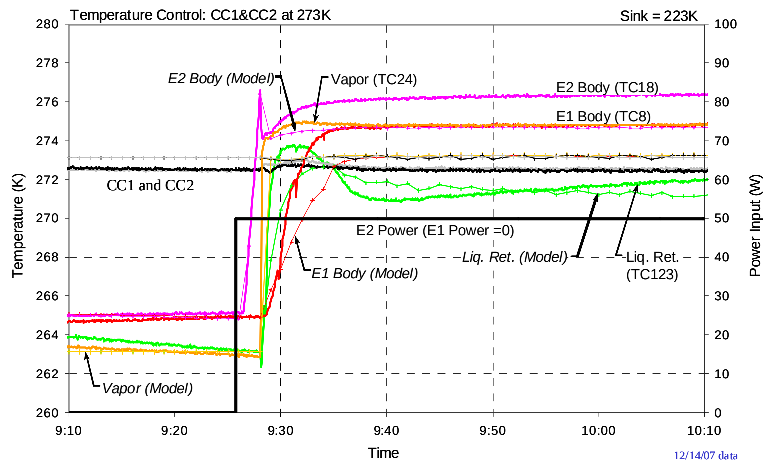

Figure 14. Loop Temperatures During a Start-up Test at 273K with 0W/50W to E1/E2)

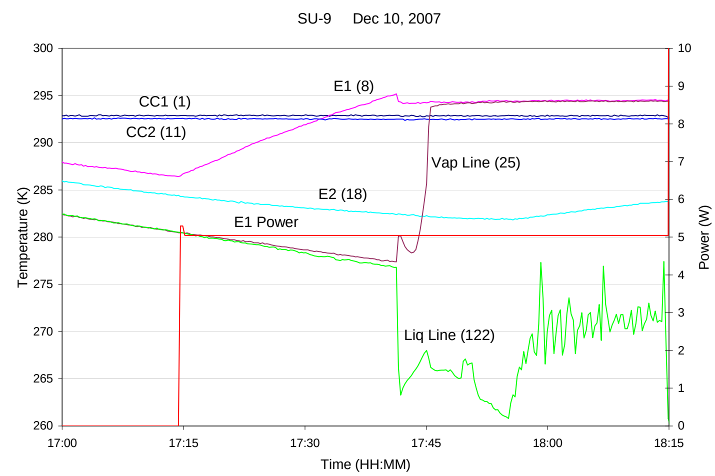

Figure 15. Start-up with 5W/0W at 293K

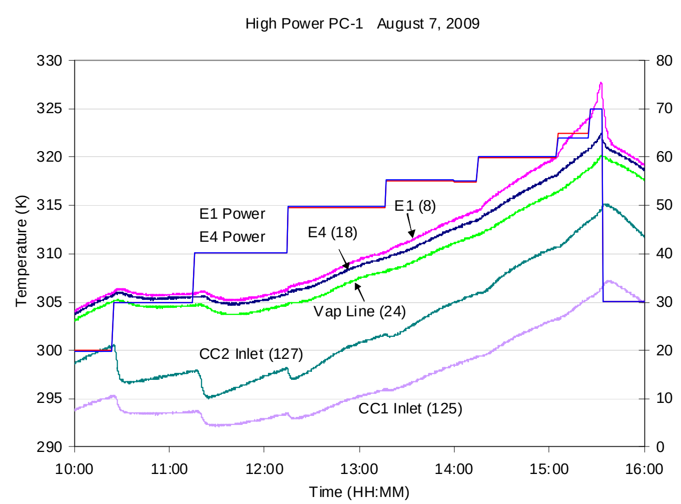

Figure 16. High Power Test Without CC Temperature Control

Figure 17 shows loop temperatures during a power cycle test where both CCs were kept at 308K by the TECs and the cryopanels were maintained at 173K. The heat load to E1/E4 was varied as follows: 75W/0W, 50W/25W, 25W/50W, 0W/75W, 5W/50W, 50W/5W, 50W/50W, and 60W/60W. Despite some large variations in the heat load, the TECs were able to control both CC temperatures at the set point temperature of 308K. The temperatures of E1 and E4 varied with the heat load to each individual evaporator due to the heat transfer requirement. This test also demonstrated once again that the loop could transport up to 120W of total heat load (60W/60W to E1/E4).

Figure 18 shows the loop temperatures where the temperatures of Radiator 1 and Radiator 2 were varied independently by setting their control heaters at different set point temperatures. Both CC1 and CC2 were controlled at 293K by TECs, and an uneven heat load of 30W/10W was applied to the E1/E2 thermal masses. The set point temperatures of control heaters for Radiator 1/Radiator 2 were varied as follows: 223K/223K, 298K/223K, 303K/223K, 223K/223K, 223K/298K, 223K/303K, and 223K/223K. The CC1/CC2 temperatures were maintained within ±1K of the set point temperature and E1 and E2 temperatures were unaffected by the radiator temperature variations. The flow regulator automatically balanced the heat dissipations between the two condensers. When the temperature of one radiator was raised above the CC saturation temperature, the flow regulator was able to stop the vapor from entering the liquid line throughout the test as evidenced by the subcooled temperature of the liquid line immediately downstream of the condensers (TC119).

Figure 19 depicts loop temperatures during a CC set point change test. In the first part of the test, a heat load of 52W/5W was applied to E1/E2 thermal masses (or instrument simulators, "IS1" or "IS2" on the figure). The temperature inside the thermal vacuum chamber surrounding the evaporators/CCs, thermal masses, and vapor and liquid lines, was about 283K. The TECs were able to keep both CCs at 273K. The temperatures of both CCs were raised from 273K to 298K in steps with 5K increments. Evaporators E1 and E2

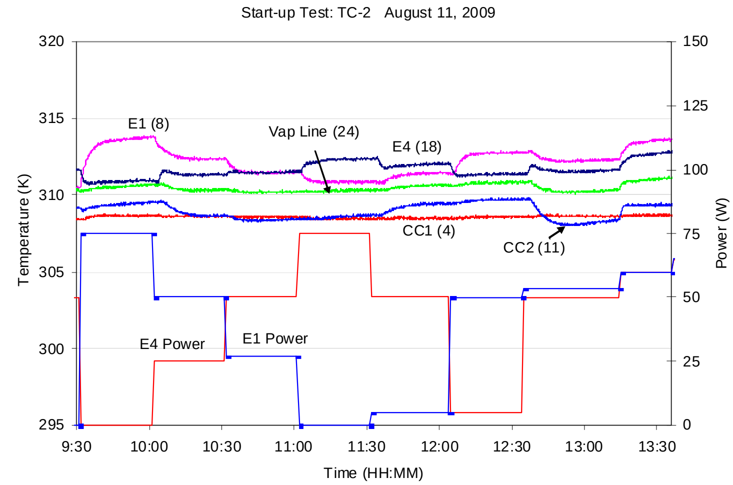

Figure 17. Power Cycle Test with Uneven Power at 308K

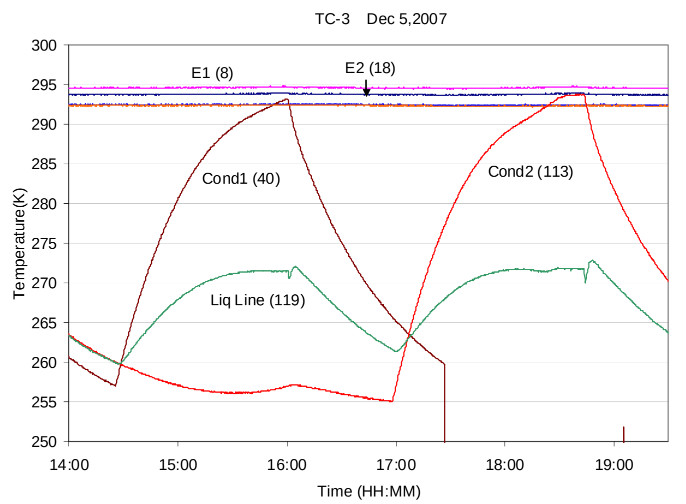

Figure 18. Flow Regulation Test with Uneven Power at 293K

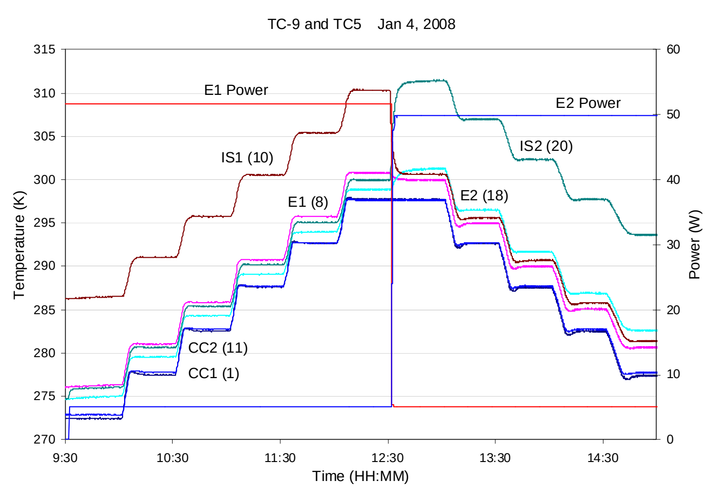

Figure 19. CC Set Point Change Test

and their thermal masses rose in temperature in tandem with the CC temperature rise. In the second part of the test, a heat load of 5W/50W was applied to E1/E2 thermal masses. The temperatures of both CCs were decreased in steps with 5K increments. Again, Evaporators E1 and E2 and their thermal masses decreased in temperature with the CC temperatures. This test demonstrated the ability of the CCs to control the loop operating temperature when the temperatures of the CCs were changed.

For TRL 6 validation with the proto-flight unit, no active cooling was provided to the evaporator thermal mass during the heat load sharing test. Instead, the heat load sharing operation was verified qualitatively by applying power to one of the evaporator thermal masses and then raising the CC set point temperature in steps. If the temperature of the un-powered evaporator also rises near the newly set CC temperature, one can infer that the heat source comes from the vapor generated by the powered evaporator, thus demonstrating the heat load sharing function. Figure 20 shows the results of such a heat load sharing test where a heat load of 30W was applied to E1, and the CC1 set point temperature was increased from 278K to 313K in steps with 5K increments. As the CC1 temperature increased, the powered evaporator E1 and its thermal mass (IS1) rose in temperature as expected. In addition, the unpowered evaporator E2 and its thermal mass (IS2) also rose to near the CC1 temperature, indicating that E2 did receive heat from E1 via the vapor that was generated. Also shown in the figure are the analytical model predictions of the temperatures of the CCs, evaporators, and thermal masses. The model predictions were in excellent agreement with the experimental data.

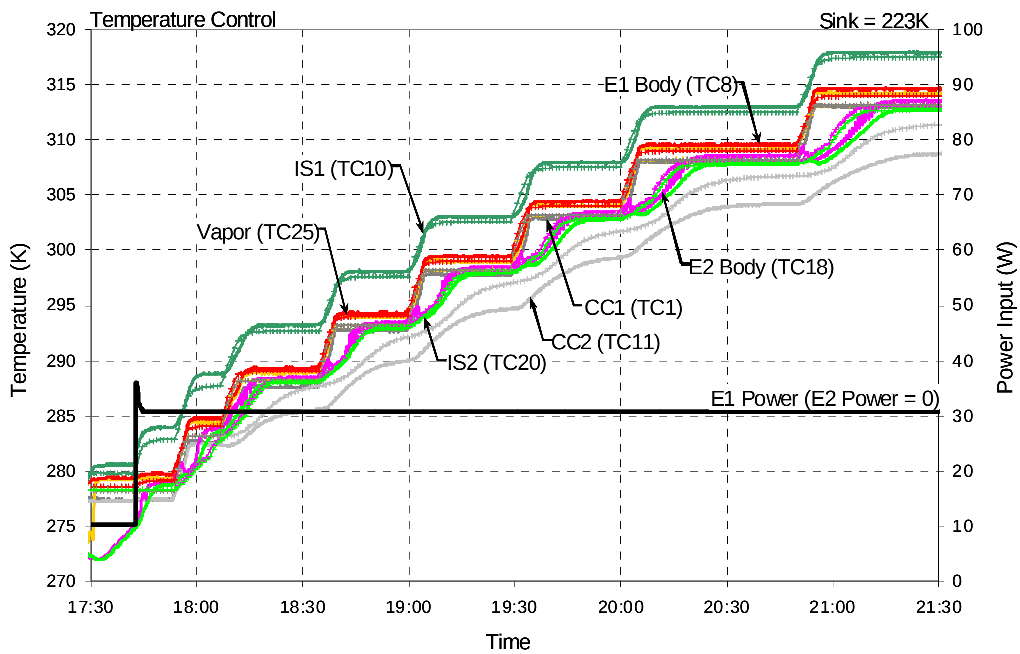

Figure 20. Comparison of Analytical Model Predictions (Thin Lines) and Experimental Data (thick Lines) of Heat Load Sharing Test HLS-3

VII. Conclusion

Under NASA's New Millennium Program Space Technology 8 (ST 8) Project, the Thermal Loop experiment has been conducted to advance the maturity of the Thermal Loop technology from TRL 3 to TRL 6. The Thermal Loop consisted of an MLHP with multiple evaporators and multiple condensers to transport heat, and TECs to control the MLHP operating temperature. An MLHP Breadboard was built and tested for TRL 4 and TRL 5 validation, and an MLHP proto-flight unit was built and tested to verify the attainment of TRL 6. In addition, an LHP analytical model was developed to predict the behaviors of the MLHP and to correlate with experimental data in all TRLs.

The MLHP Breadboard and the MLHP proto-flight unit demonstrated excellent performance in all TRL verification tests. The loop started successfully and operated stably under various evaporator heat loads and condenser sink temperatures. The TECs could keep the loop operating temperature within ±0.5K of the desired set point temperature at all power levels and all sink temperatures. The un-powered evaporator would automatically draw heat from the other powered evaporator, demonstrating the heat load sharing function. The CC control heater power was reduced by more than 50 percent when TECs and coupling blocks were used instead of electrical heaters. The flow regulators could regulate the heat dissipation among the radiators, and stop vapor from entering the liquid line when one of the condensers exhausted its heat dissipating capability. Predictions of the LHP analytical model agreed very well with experimental data in all cases that were correlated.

The Thermal Loop experiment has successfully demonstrated the attainment of TRL 6, and is ready to be flown for a space flight experiment when such an opportunity arises.

Acknowledgments

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